A Literature Survey of Alternative Refrigerants During Single Phase Heat Transfer

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ABSTRACT

A number of new alternative refrigerants have been proposed in the past several years to replace the existing refrigerants used in air-conditioning equipment. In order to study these refrigerants extensively an in-depth knowledge of their single-phase heat transfer characteristics and thermodynamic properties is needed. This paper provides a literature review of current research that has been conducted on single phase flow for alternative refrigerants, addresses a number of relations for determining the thermodynamic properties of these alternative refrigerants, and discusses their sensitivity to uncertainty. Finally, an overview of some of the current research that has been conducted on various enhancements and refrigerant / oil mixtures is provided as well.

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EXECUTIVE SUMMARY

The following items summarize the results of the information obtained from this literature survey.

1. Essentially no information is available in peer-reviewed journal publications on single phase flow for newer refrigerants.

2. Common correlations for single phase flow are applicable for refrigerants, however, the high laminar Reynolds number range to the low turbulent Reynolds number range ($200<Re<5000$) is a region with high uncertainty. The uncertainty is due to lack of experimental data in this region. Additional data, however, may not significantly reduce the uncertainty for practical application because of the sensitivity of transition region flows to sources of flow instability (return bends, solder joints, couplings, etc.).

3. Thermodynamic and transport property information should be carefully examined and a standard reference should be chosen before any single phase heat transfer study is undertaken. Property relations should also include a standard methodology for calculating mixture properties. Property uncertainties affect the accuracy of heat transfer predictions in two ways. First, experimental results and resulting correlations are dependent on properties used. Second, actual calculation of heat transfer is dependent on properties.

4. Microchannels exhibit similar characteristics to larger tubes in single phase flow. No special treatment or changes are required in order to use common correlations with microchannels, however, the small diameter range of microchannels may lead to flows that are in the transitional Reynolds number range where the highest degree of heat transfer uncertainty exists.

5. Information on microfinned tubes with refrigerants in single phase flow is sparse. Literature results generally show that heat transfer performance of microfinned tubes is dependent on the specific characteristics of a tube (fin pitch, helix angle, fin height).

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INTRODUCTION

The cooling effects of a vapor-compression refrigeration cycle are accomplished by evaporating and condensing the refrigerant at low and high pressure states, respectively. An ideal system operates entirely in the two-phase region, however, this is not practical for the actual system. The dry compression is carried out entirely in the single-phase vapor region, to avoid erosion damage within the compressor. In addition, the outlet phase of the condenser is slightly sub-cooled, residing in the liquid phase. The single phase heat transfer for the superheated vapor and subcooled liquid regions of the evaporators and condensers are important aspects of an efficient vapor-compression refrigeration cycle. Accurate thermodynamic properties of refrigerants are essential for determining the energy efficiency and capacity of a vapor-compression cycle. In addition, their transport properties are needed for the design of the equipment and its economic feasibility. With the advent of alternative refrigerants, accurate correlations and a knowledge of their sensitivity to uncertain properties, mass flow rates, and other parameters are needed for a thorough analysis of a system's design and performance. Furthermore, the determination of the heat transfer in enhanced tubes becomes more difficult when the thermodynamic properties of alternative refrigerants are uncertain.

This paper provides a literature review of current research that has been conducted on single phase flow for the alternative refrigerants R22, R134a, R410A, R407C, R404A, R502, and R507A. In addition, this paper cites a number of correlations for determining the thermodynamic properties of these alternative refrigerants and discusses their sensitivity to uncertainty. Finally, an overview of some of the current research that has been conducted on various enhancements and refrigerant / oil mixtures is provided as well.

QUANTITY OF RESEARCH AND WHERE

The largest percentage of research found, pertaining to the scope of this literature search, was conducted on R134a and R22, while significantly lesser percentages of research was found for R407C, R404A, R502, and R507; and nothing was found for R410A. Research results have begun appearing in conference literature this year, however. The United States has performed the most research on alternative refrigerants, with Canada and Germany as other major contributors. Of the most relevant literature found, 37% was from North America, 26% was from Europe, 24% was from Asia, 5.5% was from Eastern Europe and Russia, 5.5% was from the Middle-East and South-Eastern Europe, and 2% was from the South Pacific.

Hundreds of titles and abstracts have been viewed. Single phase heat transfer research with the new generation of refrigerants is very sparse in peer-reviewed journal literature. Most information related to newer refrigerants describes thermodynamic, transport properties, and two-phase flow characteristics. Because of the importance of property determination for successful prediction of heat transfer, papers describing refrigerant properties have been included in this survey.

DISCUSSION OF REFRIGERANT INFORMATION

A general description of property effects on heat transfer predictions is presented below. Some additional information regarding property determination is also included. Information obtained on specific refrigerants are included in the subsequent sections. A final subsection is included that describes single phase heat transfer results from research at the University of Illinois Air Conditioning and Refrigeration Center (ACRC). These single phase results were auxiliary parts of larger two-phase flow investigations.

General Property Discussion

Casual application of property information is a primary source of error for determination of heat transfer. A simple relation for estimating heat transfer coefficient error in turbulent single phase flow due to property inaccuracies can be derived from the Dittus-Boelter heat transfer relation:

$$h/h_{act} = (\mu/\mu_{act})^{-0.47}(k/k_{act})^{0.67}(c_p/c_{pact})^{0.33}(\rho/\rho_{act})^{0.8}$$

where
- h = predicted heat transfer coefficient
- h_{act} = actual heat transfer coefficient
- μ = predicted dynamic viscosity
- μ_{act} = actual dynamic viscosity
- k = predicted thermal conductivity
- k_{act} = actual thermal conductivity
- c_p = predicted specific heat
- c_{pact} = actual specific heat
- ρ = predicted density
- ρ_{act} = actual density

The overall inaccuracy depends on the mix of errors for each property. In an extreme case where all property errors can contribute in a manner that maximizes the error (e.g., higher than actual conductivity, density and specific heat; lower than actual dynamic viscosity. A 10 percent error in each property, for example, leads to heat transfer coefficient errors of +/- 23 percent.

A table with properties obtained from two sources (NIST "Refprop" software, version 4.01, 1993 and F-Chart Software, Inc. "EES" software, version 4.412, 1997) for R134a and R22 at 20C in the saturated liquid and saturated vapor states is shown below.

	T	P	density		c_p		μ		k	
	(C)	(kPa)	(kg/m^3)		(kJ/kg-K)		μpoise		W/m-K	
R134a			EES	Refp	EES	Refp	EES	Refp	EES	Refp
vapor	20	571.5	27.9	27.3	1.013	0.903	119	119	.0141	.0137
liquid	20	571.5	1226	1224	1.381	1.390	2618	2247	.0902	.0837
R22										
vapor	20	911	38.4	38.3	0.816	0.760	131	128	.0115	.0112
liquid	20	911	1213	1208	1.216	1.216	2096	1801	.0902	.0910

The ratio of heat transfer coefficients between the two property references is between +/- 7 percent. It is interesting to note that the best agreement is for liquid R134a which has large disagreement between viscosity and thermal conductivity. A designer who chooses properties from different sources (e.g., viscosity from a publication that used one property reference and thermal conductivity from a publication using a different property reference), the error increases to 13 percent.

The quantity of research on alternative refrigerants is somewhat limited. However, a journal article by Mark O. McLinden[1], "Thermodynamic Properties of CFC Alternatives: A survey of the available data", attempts to compile, evaluate, and correlate certain thermodynamic properties for a number of alternative refrigerants, including R22 and R134a. The article considers the critical and triple point parameters, vapor pressure, saturated liquid density, ideal gas heat capacity, and the singlephase pressure-volume-temperature (p-v-T) properties. The correlations were chosen for convenience. Consequently, the correlations may not be the most accurate of those available. The correlation used for the vapor pressure was given by Friend et al.[2]. The coefficients for each of the correlations are provided in tables for R22, R134a, and a number of other alternative refrigerants in McLinden's paper. The p-v-T data was also provided for each of the refrigerants.

In regards to R22, the correlation provided for the saturated liquid density was in strong agreement with the data provided by Zander[3]. The ideal gas heat capacity values presented in the JANAF tables[4] were in strong agreement with the correlation and considered the most reliable by McLinden. Furthermore, the p-v-T data provided by Zander[3] is supposedly the most wide-ranging, however, little data is provided for the liquid phase below 300 K and there is none for below 250 K.

Furthermore, McLinden states a number of data sources that agree well with the correlations and span a wide range of temperatures. In addition, he states which sources of data did not agree well and consequently were not used in the fitting of the coefficients.

R134a

The most research concerning CFC alternatives has occurred on R134a. Consequently, considerable data has become available. The two equations of state that have been used most widely with confidence are the Schmidt-Wagner[5] equation of state (SWEOS) and the modified Benedict-Webb-Rubin equation of state (MBWREOS) originally proposed by Jacobsen and Stewart as cited by Huber and McLinden[6]. Both of these equations have 32 terms, covering a wide range of temperatures, and are applicable to both the liquid and vapor regions. However, even though the MBWREOS is not valid in the near-critical region, the SWEOS overcomes this deficiency. In addition, the SWEOS is slightly better than the MBWREOS in representing the speed of sound and isochoric heat capacity. All of the thermodynamic properties of a fluid can be determined from correlations based on the SWEOS provided by McLinden et al.[7].

The MBWREOS has been widely used for hydrocarbons and common inorganics. The 32 coefficients of the MBWREOS for R134a were originally presented by McLinden et al.[7] in 1989 and were refit with new data in 1992 by Huber and McLinden[8].

According to Huber and Ely[9], "The most accurate approach to modeling properties of single phase fluid mixtures arises from combining a molecularly based corresponding states theory with a highly accurate empirical equation of state." Consequently, an extensive knowledge of the intermolecular potential is not required with this approach. The accuracy of the empirical reference fluid equation of state and of the shape factors used to define the equivalent substance state point dictate the accuracy of this approach. Huber and Ely chose to use the 32-term Jacobsen-Stewart[2] type MBWREOS for R134a. The shape factors for other refrigerants were determined by mapping their saturation boundaries onto the reference fluid, R134a, to develop expressions for the shape factor relative to R134a.

Experimental data for the basic properties of R134a has been collected to permit comparisons and verification of proposed equations of state, such as the SWEOS and the MBWREOS. The following authors have made contributions to the collection of experimental data for properties of R134a. Experimental data for the vapor pressure of R134a has been collected by Basu and Wilson[10], Kubota et al.[11]., Magee and Howley[12], Lavrenchenko et al.[13], Piao et al.[14], and Weber[15]. Experimental data for the density of R134a has been collected by Hou et al.[16], Kabata et al.[17],Maezowa et al.[18], and Wilson and Basu[19]. To provide redundancy and reduce the propagation of systematic errors in properties derived from density and heat capacity alone, Guedes and Zollweg[20] recorded the speed of sound in liquid R134a. Experimental data for the heat capacity of R134a has been collected by Magee[21], and Saitoh et al.[22] Experimental data for the heat transfer coefficient for R134a has been collected by Eckles and Pate[23], Schlager et al.[24], and Singh et al.[25] Experimental data for the thermal conductivity of R134a has been collected by Gross et al.[26], Krauss et al.[27], Laesecke et al.[28], Ross et al.[29], Rouvinski et al.[30], and Tsvetkov et al.[30] Stegou-Sagia[31] provides a compilation of properties, including: vapor pressure, saturated liquid density, viscosity, latent heat of vaporization, saturated liquid thermal conductivity, and surface tension. Finally, Preisegger and Henrici[32] discuss the chemical properties, material compatibility, and thermodynamic properties of R134a. De Rossi et al.[33] present a software package that can compute thermodynamic properties of 20 working fluids and analyze vapor compression systems. Stegou-Sagia and Katanos[34] calculated the real-gas isentropic exponents $k_{p,v}$, $k_{v,T}$, and $k_{p,T}$ for R134a and a number of other alternative refrigerants. The MBWREOS was used for this study.

Eckels and Pate[35] experimentally determined the heat transfer coefficients for R134a during in-tube single-phase flow, evaporation and condensation. These coefficients were determined for a horizontal smooth tube with an 8.0 mm inner diameter and 3.67 m length. The mass flux was varied form 125 to 400 kg m^{-2} s^{-1}. The evaporation and condensation tests compared the experimental heat transfer coefficients to a number of correlations. The comparisons revealed that the Chaddock-Brunemann[36] and Kandlikar[37] correlations differed by less than ±15% from the experimental evaporation heat transfer coefficients. Furthermore, the Shah[38], Traviss et al[39], and Cavallini and Zecchin[40] correlations all differed by less than ±25% of the experimental condensation heat transfer coefficients. However, Eckels and Pate added that these correlations tend to under predict the heat transfer coefficients at low mass fluxes and over predict at larger mass fluxes. The liquid single phase heat transfer coefficients were determined for temperatures ranging from 24 to 27°C and mass fluxes ranging from 500 to 900 kg m^{-2} s^{-1}. The Nusselt number was experimentally determined for R134a and compared with the Dittus-Boelter-McAdams[41] and Petukhov-Popov[42] correlations. Eckels and Pate found that the Petukhov-Popov correlation was within 2.5% of the experimental Nusselt number, where as the Dittus-Boelter-McAdams correlation was within 24%. They further added that the Petukhov-Popov correlation was accurate for R22 as well.

R22

Before 1992, Kohlen's[43] equation of state for R22 was regarded as the most accurate and reliable, since it was developed by data taken by Kohlen himself. In addition, the equation of state by Kamei et al.[44] was considered one of the most accurate with 28 coefficients that were fitted to thermal and caloric data as well as the Maxwell criterion. However, a new equation of state by Wagner et al.[45] for R22 is the fundamental equation that is expressed in the form of the Helmholtz energy with the density and temperature as two independent variables. This equation contains 22 fitted coefficients and covers the entire fluid region from 116 K (triple point temperature) to 550 K with pressures up to 200 mPa. The mathematical structure of this equation was optimized through procedures and multi-property fitting techniques discussed in Saul and Wagner[46] as well as Setzmann and Wagner[47]. This new equation goes beyond all previous equations in terms of lower uncertainty and range of validity. This equation also encorporates new liquid region pressure, density, and temperature data, new vapor pressures, saturated liquid densities, and speed of sound data.

Jung and Radermacher[48] performed a study on predicting the heat transfer coefficient and pressure drop of a few refrigerants, including R22. Within this study they performed an analysis of the effects of uncertainties in transport properties on the heat transfer. This study revealed that heat transfer prediction is more sensitive to liquid transport properties than those of the vapor. Jung and Radermacher[48] state that typical uncertainties of 10.0% in the transport properties yields a change of less than 6% in the heat transfer coefficient prediction. This would generally be true for random inaccuracies of property information, however, a kinematic viscosity that is 10 percent greater than actual and a thermal conductivity 10 percent less than actual would lead to a heat transfer coefficient that is 12 percent in error.

The following authors have made contributions to the collection of experimental data for the thermodynamic properties of R22. Diller et al.[49] recorded the viscosity of saturated liquid R22 at temperatures between 120 and 320 K. Diller et al.[49] state that the recorded data agrees well with an empirical fluidity - volume equation. Agarwal et al.[50] estimated the thermal conductivity, viscosity, and specific heat of both liquid and vapor R22. Srinivasan[51] proposes a saturated liquid density correlation for cryogenic liquids, which includes R22. Kohlen et al.[52] also reports on thermophysical properties of R22.

R404A

In the process of analyzing a conventional solar air heater and two serial solar-assisted heat pump systems, Abou-Ziyan et al.[53] used the thermodynamic properties published by the International Institute of Refrigeration[54,55] for R22 and R134a, and by Hoechsf[56] for R404A, to perform a regression analysis. This resulted in a number of correlations that are valid from -50° C to the near critical points for each refrigerant, with correlation factors higher than 0.99. Their study showed a 23% increase in R134a's coefficient of performance over R404A.

R407C

The amount of literature on R407C is rather limited compared to R22 or R134a. In the process of evaluating the twophase heat transfer coefficient and pressure drop characteristics of R22 and R407C in a 9.52 mm micro-fin tube, Kuo and Wang[57] provide a comparison of the thermodynamic properties of these two refrigerants. This comparison showed that the transport properties of R407C and R22 were fairly similar at the evaporation pressure of 600 kPa. In addition, Mongey et al.[58] concluded that R407C was a suitable replacement for R22 in counter-current heat exchangers at higher evaporator temperatures.

This survey of literature did not find any studies pertaining to single-phase heat transfer of R407C. As a result, further studies could be pursued in this area.

R502

Only a few articles were found concerning R502 during this search of current literature, with those of Sami and Tulej[59,60] emerging as the most informative. However, these articles concerned drop in replacements for R22, R502, and R12. As a result, further studies could be pursued to establish more accessible data on R502's single phase characteristics and thermodynamic properties.

In the process of evaluating a new drop-in replacement blend for R22 and R502, Sami and Tulej[59] used an improved Carnahan-Starling-DeSantis (CSD) equation of state, given in Morrison and McLinden[61], to evaluate the thermodynamic properties of these refrigerants. Sami and Tulej[60] have concluded that their drop-in replacements NARM-22, NARM-502, and NARM-12 are viable alternatives for R22, R502, and R12, respectively, and meet the standards set forth by UNEP.

R507

Lavrenchenko et al.[62] provide experimental data for the phase equilibrium states and thermodynamic properties for an azeotrope named "R507", however, their mixture was based on R152a and R218.

Sami and Song[63] reported that R507 (R32/R125/R143a/R134a with mass percentages of 40/25/25/10) has a higher heat transfer coefficient over most other refrigerants in evaporation and condensation. They attributed this to R507's high concentration of R125.

ACRC Single Phase Results

Three investigations at the University of Illinois provide information on single phase flow with R134a. Wattelet et al.[73] and Dobson[74] examined the Dittus Boelter, Petukhov, and Gnielinski single phase heat transfer relations and found reasonable agreement among all three relations for R134a for Reynolds numbers ranging from 2000 to 30,000. The Petukhov relation tends to give slightly higher Nusselt number predictions overall. The Dittus Boelter relation is similar to the Petukhov relation for the 2000 to 5000 Reynolds number range, and is then somehwat lower than either of the other two relations. The Gnielinski relation is similar, but somewhat lower than the Petukhov relation for Reynolds numbers greater than 5000. The Gnielinski relation tends to give low Nusselt numbers at low Reynolds numbers. Huen[75] discusses the Gnielinski relation in detail for single phase flow in microchannels. Gnielinski's correlation appears to have been weighted toward higher Reynolds numbers and its use at Reyonolds numbers lower than 5000 should be treated with caution. Huen also discusses single phase heat transfer in microchannel passageways with hydraulic diameters of 1.494 mm. All flow characteristics observed for liquid phase and vapor phase flows of R134a were typical of larger passageways at similar Reynolds numbers.

REFRIGERANT/OIL MIXTURES

In many vapor-compression systems the oil of the compressor may come in contact with the refrigerant and be carried from the compressor into the refrigeration system. Oil can either increase or decrease the heat transfer coefficient. Hewitt et al.[64] studied the effects of compressor lubricants circulating in refrigeration systems and reported on the performance of different alternative refrigerants. Hewitt et al.[64] found that the heat transfer coefficient decreased in most cases. Hambraeus[65] studied the effects of three different ester-based oils on the heat transfer coefficient of R134a in a horizontal evaporator and also found that the heat transfer coefficient decreases overall. In addition, Shao and Granryd[66] found the heat transfer coefficient to depend upon the definition of the saturation temperature. Neglecting the effects of oil on the vapor pressure of R134a, they found that the oil has little effect on the heat transfer coefficient. However, while using the saturation temperature of the refrigerant-oil mixture, they found the heat transfer coefficient to decrease with increasing oil concentrations. Using R12 and R22, Cawte et al.[67] showed that 2% of Shell Calvus 32 oil can increase the heat transfer coefficient of the refrigerant by 12% for a complete evaporator. However, they found that concentrations greater than 2% provided lower gains in heat transfer and an oil concentration of 10% provided no gain in heat transfer.

ENHANCEMENTS

Micro-fin tubes are relatively inexpensive to produce, which has increased their popularity. According to Kuo and Wang[57], "One of the reasons for the growing popularity of the micro-fin tube is the larger heat transfer enhancement relative to the increased pressure drop. Generally, a 50-100% increase in evaporation and condensation heat transfer occurs, while only a 20-50% increase in pressure drop was recorded for various kinds of refrigerants." Chiang[68] reported that the evaporation heat transfer coefficient increases with increased tube diameter; whereas the condensation heat transfer coefficient decreases. However, investigations of the single-phase heat transfer with the micro-fin tube are not well correlated and require further studies. Heat transfer coefficients have not been recorded for Reynold's numbers below 10,000, which is a range that is encountered often in air conditioning systems. More research is needed for the single phase heat transfer characteristics for $2500 < Re < 40{,}000$.

Wang et al.[69] studied single-phase heat transfer and pressure drop of refrigerants in 9.52, 7.94, and 7.0 mm micro-fin tubes. According to Wang et al.[69], the Dittus-Boelter correlation is only valid with micro-fin tubes for Reynold's numbers greater than 10,000. Furthermore, the heat-momentum transfer analogy has been shown to correlate better than the Dittus-Boelter for lower Reynold's numbers and may also be used for any basic roughness type.

Using 9.52 mm tubes in a double-tube counter flow condenser with flow rates of 26-27 kg/h, Koyama et al.[70] also reported heat transfer improvements for grooved tubes. For pure refrigerants, they found the local Nusselt number to be 60% higher for grooved tubes than smooth tubes.

Sami et al.[71] developed a numerical model for predicting refrigerant mixture liquid filmwise condensation inside enhanced surface vertical cylinders. The model assumes one dimensional flow. An improved Carnahan-Starling-DeSantis equation of state[61] was used to determine the thermodynamic properties of mixtures. The model predicted condensation for R502 on inside and outside surfaces of cylinders with rectangular fins within 20%. The model predicted condensation for binary and ternary refrigerant mixtures also within 20%.

Schlager et al.[72] studied the evaporation and condensation performance of R22 in 12.7 mm micro-fin tubes and compared the results with a smooth tube for mass fluxes of 75-400 kg/m^2-s. For evaporation the micro-fin tubes offered heat transfer coefficients 1.6-2.2 times greater than the smooth tube. Similarly, for condensation the micro-fin tubes offered heat transfer coefficients 1.5-2.0 times greater than the smooth tube. The also found the pressure drop to increase as well, but not as much as the heat transfer coefficient.

A recent investigation by Brognaux, Webb, and Chamra[76] studied systematic variations of micro-fin structures over a range of Prandtl numbers by using water and air as the heat trasnfer fluids. General results showed that a systematic procedure can be followed for characterizing the performance of micro-fin tubes.

CONCLUSIONS

A number of new alternative refrigerants have been proposed in the past several years to replace the existing refrigerants used in air-conditioning equipment. In order to study these refrigerants extensively an in-depth knowledge of their single-phase heat transfer characteristics and thermodynamic properties is needed. This literature review concludes that there is considerable information available on R134a due to the large amount of research that has been conducted upon it globally. The same is true for R22. However, considerably lesser amounts of research have been conducted on R407C, R410A, R502, and R507A. No significant amount of single phase heat transfer research has been performed with any of these refrigerants, however, available results generally show existing correlations should be suitable for predictions of heat transfer. The largest errors will be due to uncertainties in properties and for calculations in the laminar to turbulent transitional flow range.

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Appendix A
Bibliography of Conference Proceedings

The following conference proceedings have been reviewed in order to look for additional material relevant to single phase refrigerant flows. Additionally, a web-based search of the ASHRAE meetings and conferences has been completed.

19th International Congress of Refrigeration, the Hague, Netherlands, 1995

IIR Conference on CFC's, The Day After, Padova, Italy 1994

International Conference on Ozone Protection Technologies, Baltimore, MD, Nov. 12-13, 1997.

International Conference on Ozone Protection Technologies, Washington, DC, Oct. 21-23, 1996.

International CFC and Halon Alternatives Conference, Washington, D.C., Oct. 21-23, 1995.

International CFC and Halon Alternatives Conference, Washington, D.C., Oct. 24-26, 1994.

International CFC and Halon Alternatives Conference, Washington, D.C., Oct. 20-22, 1993.

International CFC and Halon Alternatives Conference, Washington, D.C., Sept.29-Oct.1, 1992.

International CFC and Halon Alternatives Conference, Baltimore, MD, Dec. 3-5, 1991.

International CFC and Halon Alternatives Conference, Frederick, MD, Nov. 27-29, 1990.

International CFC and Halon Alternatives Conference, Washington, D.C., Oct. 10-11, 1989.

International Refrigeration Conference at Purdue, W. Lafayette, IN, July 19-22, 1994.

International Refrigeration Conference - Energy Efficiency and New Refrigerants, Purdue University, W. Lafayette, IN, July 14-17, 1992.

USNC/IIR Purdue Refrigeration Conference, W. Lafayette, IN, July 17-20, 1990

Review of Conference Papers

The review resulted in many citations of a similar nature to those reported in the main text, which focused on peer-reviewed archival journal publications. Two-phase flow heat transfer and pressure drop for a variety of refrigerants also appear in these conference proceedings. Also, investigations related to properties and property predictions frequently appear. Single-phase flow of new refrigerants has not been found within abstract descriptions of these papers. Some information from some the most relevant papers are included below.

1) Krauss, R., K. Stephan, *Viscosity and thermal conductivity of R-152a,* **Proc. 19th Intl. Cong. Refrigeration**, the Hague, Netherlands, 1995, v. IVa, pp 366-374.

This paper presents correlations for viscosity and thermal conductivities of R-152a, and explains why their accuracy is limited to ±5% due not only to measurement errors, but also due to uncertainties in thermodynamic properties used to reduce the data. For R-152a Krauss et al. note that their correlations are based on fairly complete and accurate thermodynamic data, including data near the critical point. Since the accuracy of heat transfer coefficients depends strongly on the accuracy of transport property correlations, it is important for users to know the accuracy of those correlations and the accuracy of the thermodynamic property information used to reduce the data underlying the correlations.

The purpose of this paper was to update transport property correlations that the authors had developed at a time when thermodynamic data for R-152a were preliminary and incomplete. Such considerations illustrate the need for developers of transport property correlations to rely exclusively on published values of (say) thermal conductivity that are known to have been derived using accurate values of $c_p(P, T)$. The same is true for developers of heat transfer correlations. Extreme caution is therefore required in the case of new refrigerants, because some heat transfer correlations may represent curve fits of data from several sources, some of which may have relied upon preliminary inaccurate thermodynamic equations in the data-reduction process. Peer-reviewed articles in archival journals are much more likely to contain such detailed documentation than are papers in conference proceedings.

2) Latini, G., G. Passerini, F. Polonara, *Dynamic viscosity of alternative refrigerants along the saturation line,* **Proc. 19th Intl. Cong. Refrigeration**, the Hague, Netherlands, 1995, v. Iva, pp 375-382.

This paper presents a correlation for dynamic viscosity, an essential building block for any single-phase heat transfer correlation. The correlation is compared to published data for 25 refrigerants. For R23, R32, R125, 134a, 143a, and 152a the mean absolute deviations were 9%, 1%, 6%, 5%, 8%, and 4%, respectively.

3) Orekhov, I. I., A. V. Kletskii, Y. A. Laptev, O. B. Tsvetkov, *Pentafluoroethane (HFC125) equation of state and transport properties,* **Proc. 19th Intl. Cong. Refrigeration,** the Hague, Netherlands, 1995, v. Iva, pp 457-464.

This paper presents a correlation for thermal conductivity of R125, based on 18 data points and an internally-generated correlation for $c_p(P, T)$. Experimental uncertainties were estimated to be 2-3%.

4) Bivens D B., Yokozeki A., Geller V Z., Paulaitis M E., *Transport properties and heat transfer of alternatives for R-502 and R-22,* **ASHRAE/NIST Refrigerants Conference, R-22/R-502 Alternatives,** Gaithersburg, Maryland, August 1993, 73-84.
Thermal conductivities and viscosities for refrigerant mixtures identified as replacements for R502 and R22, as well as their pure-component transport properties, were measured. Correlations for calculating the thermal conductivity and viscosity were obtained from the experimental data. A method for predicting liquid thermal conductivities and viscosities for mixed refrigerants on the basis of pure-component data was developed and compared to for R502 and R22. Comparisons were made with measured heat transfer coefficients for R22, R502, and alternatives.